Physics potential of non-conventional ν beams

Neutrino Factory +

ν beams

- It has been more than 50 years since Simon van der Meer invented the magnetic horn in order to improve the performance of neutrino beam production at accelerators.
- We have not yet moved beyond this paradigm.
- Should we plan to do so?
  - Will it be necessary?
    - Better is the enemy of “Good Enough”, If it ain’t broke, don’t fix it…..
  - If so, when, how
- How, has been the primary focus of this meeting for the past 16 years

The Neutrino Factory
A VERY short review

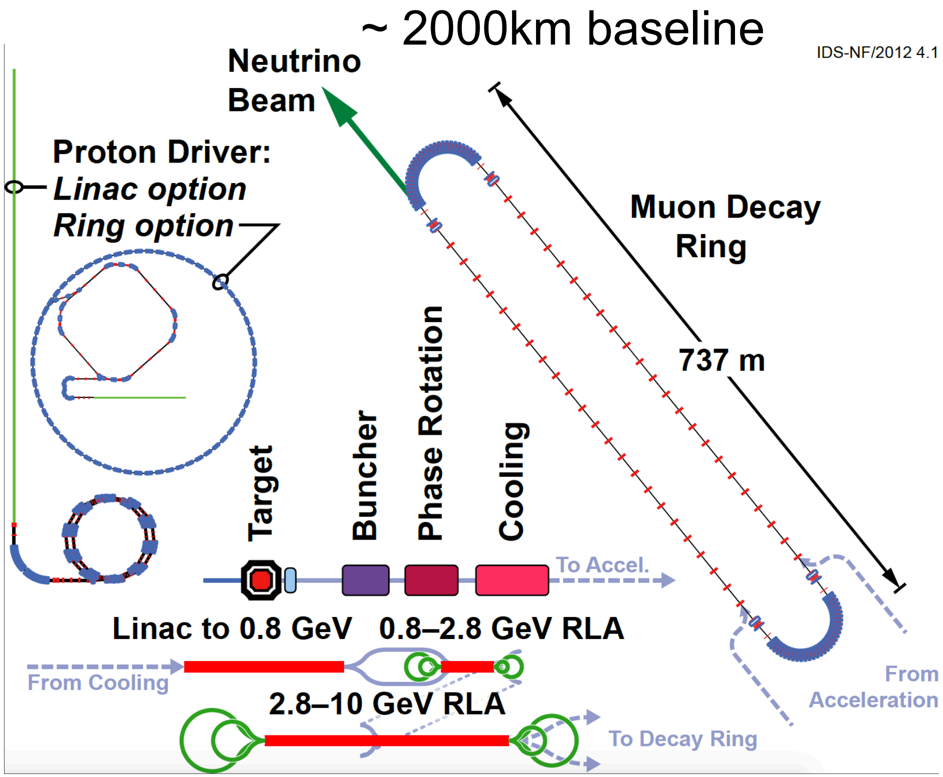
- High-power proton beam produces pions
  - Optimize for production at 300-600 MeV/c
- Utilize solenoidal capture in order to collect both π^+ and π^-
  - Simultaneous ν and ν-bar running
- Let pions decay to muons
- Cool the muons
  - Emittance reduction
  - Not absolutely required, but large (~3) increase in flux
- Accelerate muons to desired momentum
- Inject muons into a storage (decay) ring

It has been an interesting journey

- Study 1 (US-Fermilab) [2000]
- Study 2 (US-BNL) [2001]
- NuFact-Japan study [2001]
- CERN NF study [2002]
- Study 2a (APS Multidivisional Neutrino Study) [2004]
- ISS (first international study; ISS group) [2006]
- International Design Study for a Neutrino Factory (IDS-NF) [2013]

During this period, the ν physics landscape changed dramatically

Neutrino Factory
IDS-NF



This is green-field design
Site specific: NuMAX @ Fermilab

$$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \ \nu_e$$
$$\mu^- \rightarrow e^- \nu_\mu \ \bar{\nu}_e$$

- Precisely known flux & composition
  - ν flux derived from instrumentation in D.R.
  - Many factors driving uncertainties in conventional ν beams, no longer relevant
    - Secondary particle production
      - Particle types, flux and energy distribution
    - Proton beam targeting stability
    - Target/horn stability
- Flux not dependent on desired ν energy
  - Small losses due to acceleration
  - Impossible now or ever with conventional ν beam
- Interestingly, NF can now be considered "technology-ready"
  - MERIT, MuCool, MICE, EMMA

Oscillation channels at the NF

$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$	$\mu^- \to e^- \overline{\nu}_e \nu_\mu$	
$\overline{\nu}_\mu \to \bar{\nu}_\mu$	$\nu_\mu \to \nu_\mu$	disappearance
$\overline{\nu}_\mu \to \bar{\nu}_e$	$\nu_\mu \to \nu_e$	appearance (challenging)
$\overline{\nu}_\mu \to \bar{\nu}_\tau$	$\nu_\mu \to \nu_\tau$	appearance (atm. oscillation)
$\nu_e \to \nu_e$	$\bar{\nu}_e \to \bar{\nu}_e$	disappearance
$\nu_e \to \nu_\mu$	$\bar{\nu}_e \to \bar{\nu}_\mu$	appearance: "golden" channel
$\nu_e \to \nu_\tau$	$\bar{\nu}_e \to \bar{\nu}_\tau$	appearance: "silver" channel

12 channels accessible
if E_ν is above the τ threshold

Near detector physics at the NF

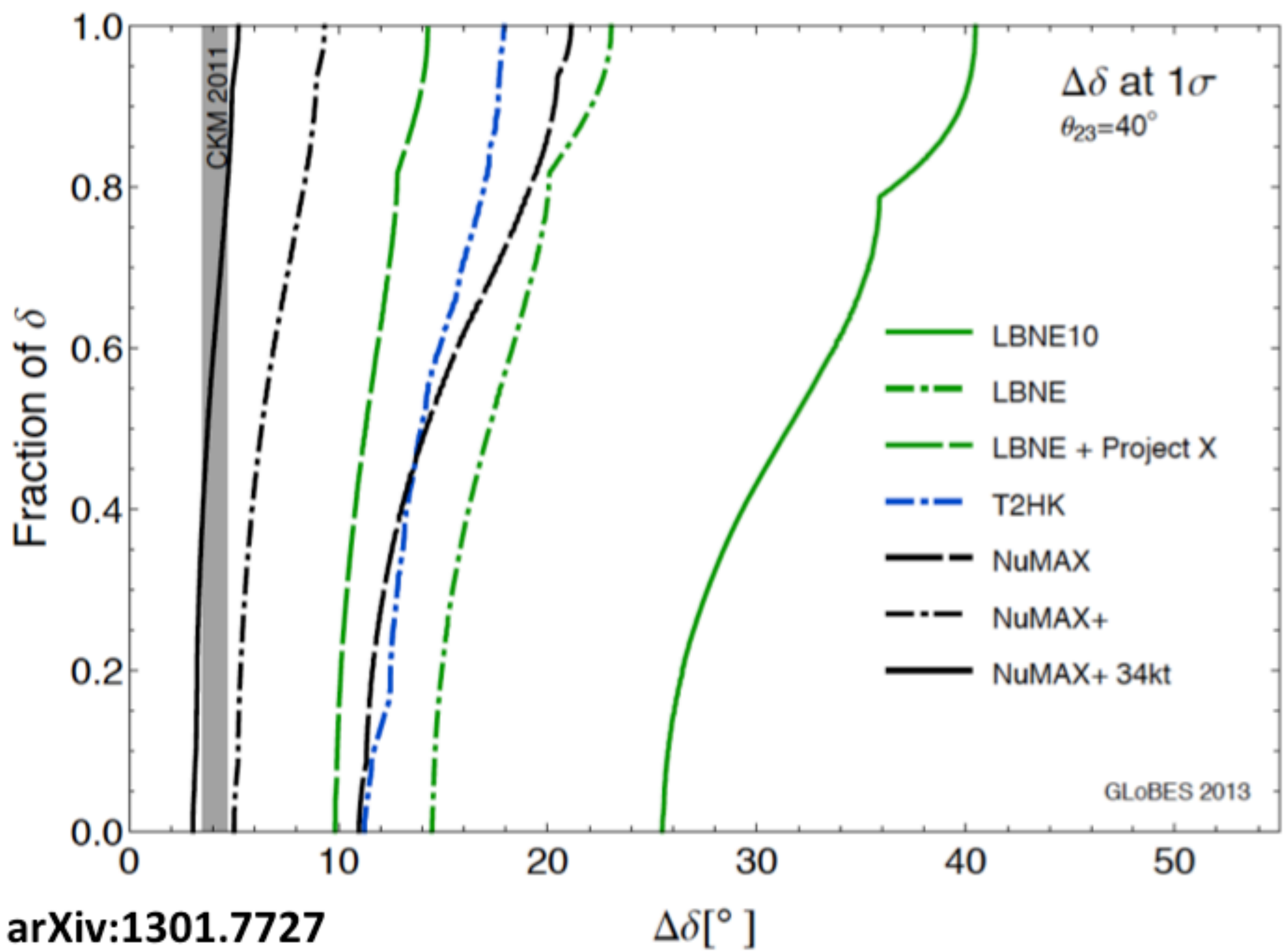
Although not a primary focus of any of the NF studies, far-reaching physics potential:

- Cross-section measurements: DIS, QES, RES scattering
  - Exhaustive study of ν_e and ν_e-bar interactions
- $\sin^2\theta_W$: $\delta\sin^2\theta_W \sim 0.0001$
- Parton Distribution Functions, nuclear shadowing
- Charm production: $|V_{cd}|$ and $|V_{cs}|$, D^0/ D^0 mixing
- Polarised structure functions
- Λ polarization
- Beyond SM searches
  - Tests of $\nu_\mu - \nu_e$ universality
  - Heavy ν
  - eV-scale pseudo-scalar penetrating particles
  - NSI

NF physics reach within the SνM

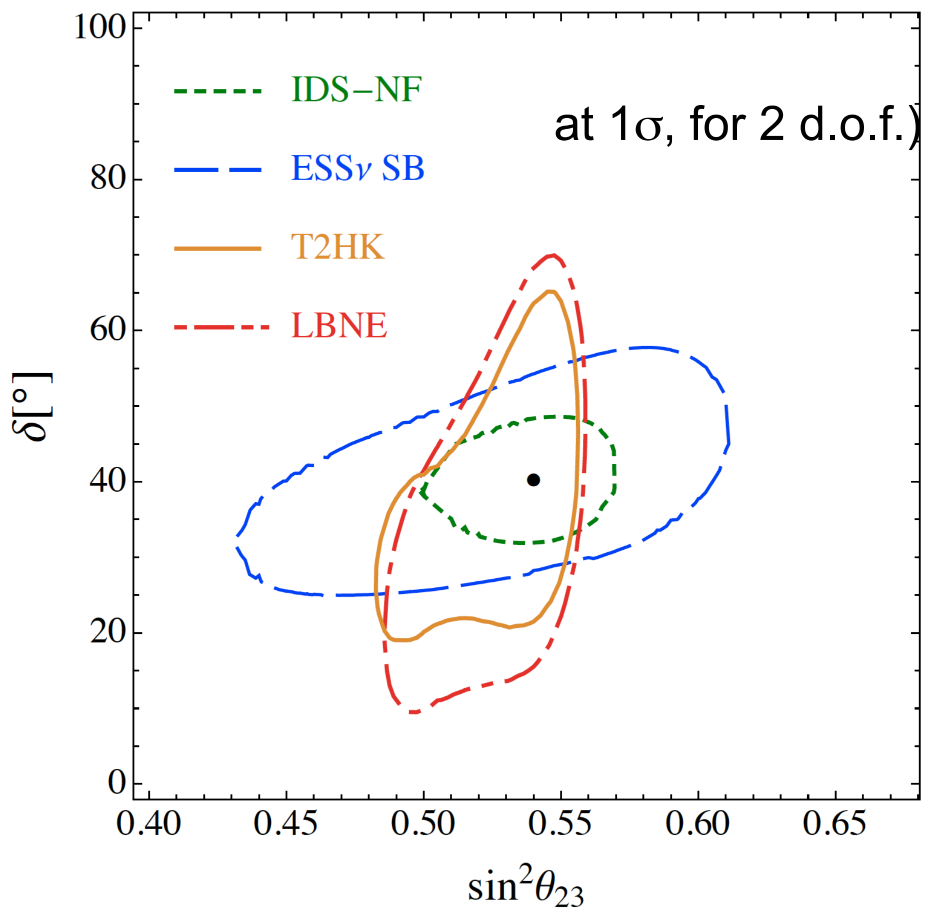
- In a post DUNE/HyperK world much of the SνM will have been exhaustively studied
  - This “era” includes data from INO, JUNO, Pingu…
- NF can:
  - Improve on the measurement of δ
  - Measurement of θ_{23} and quadrant
  - Add to ν interaction physics

Precision on δ



arXiv:1301.7727

θ_{23}



at 1σ, for 2 d.o.f.),

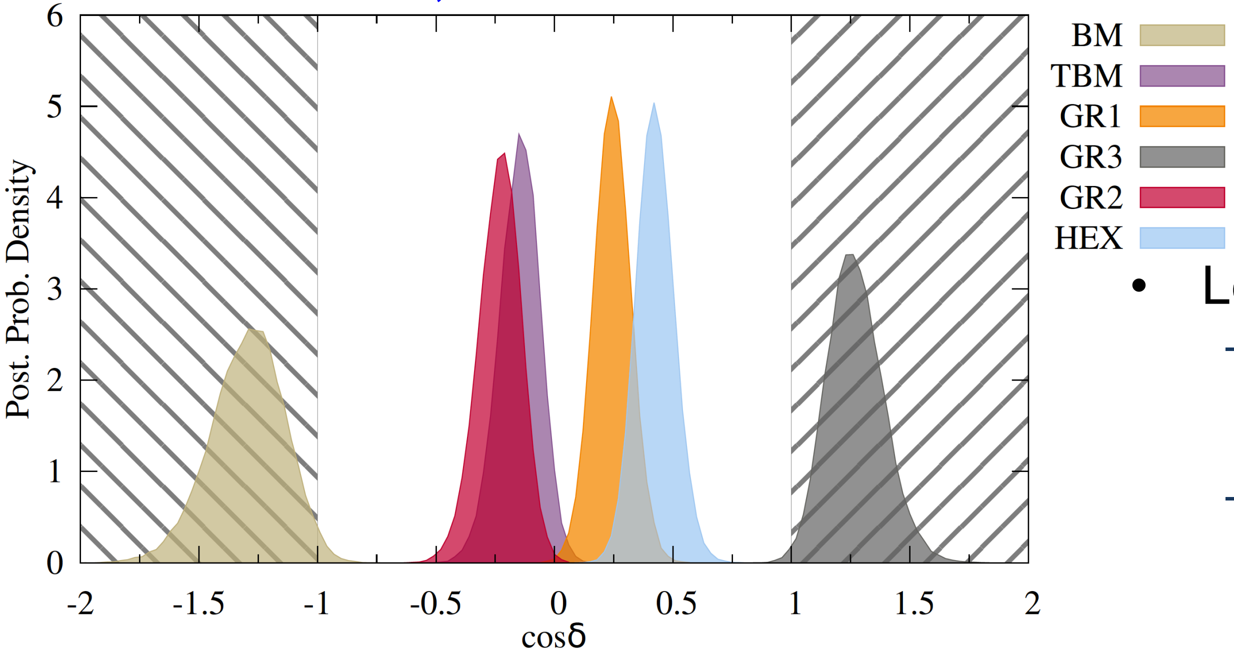
- The NF has the potential to contribute in the DUNE/ HyperK era

Coloma *et al.*, arXiv1406.2551v1

Importance of precision/ robustness

Precision's potential impact

Ballet *et al.*, arXiv:1410.7573v2

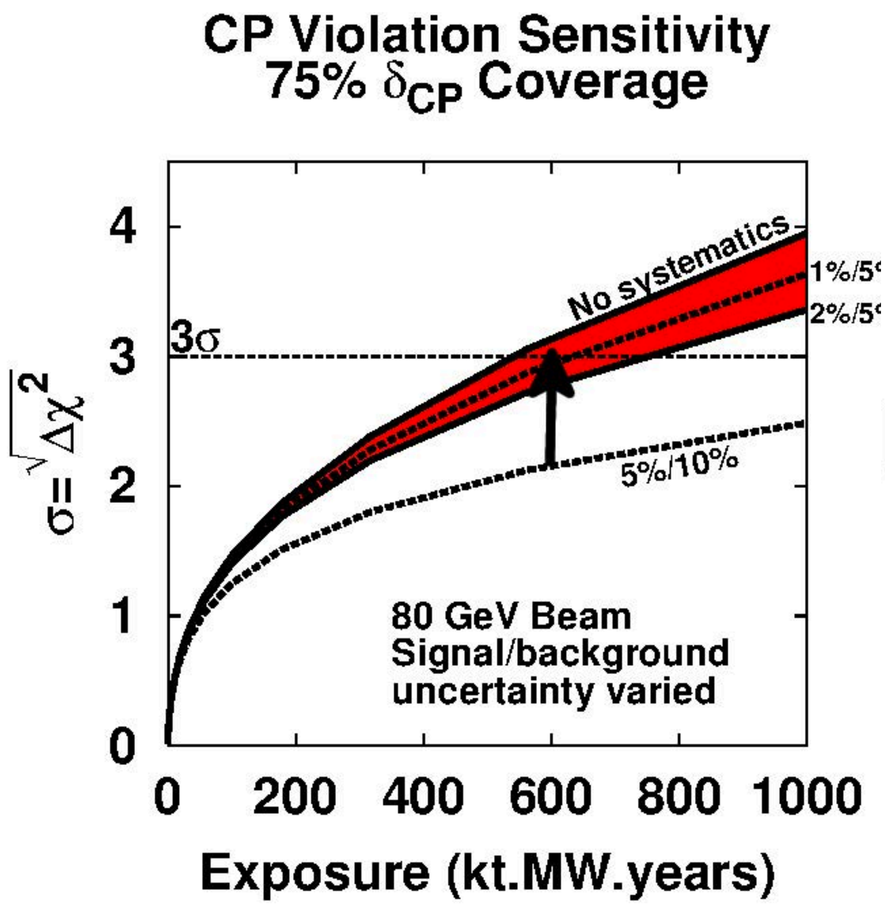


- Lepton mixing sum rules
  - Relate the three lepton mixing angles to the CPV oscillation phase δ,
  - Can shed light on the underlying symmetries since they can lead to predictions on these rules regarding their ratio mixing patterns
    - bimaximal
    - tribimaximal
    - golden
    - Hexagonal
- Path to and understanding of the underlying physics?

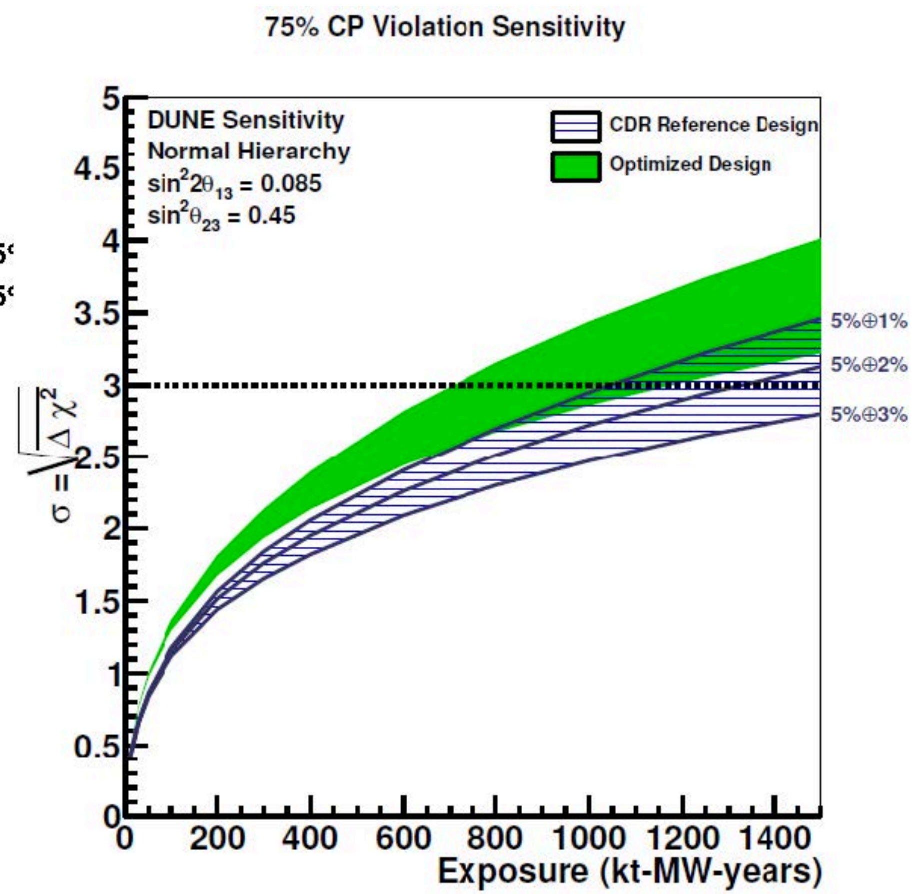
Note: the precise measurement of θ_{13} has ruled out many models.

See: C. Albright: arXiv:0911.2437v1

Missing the mark

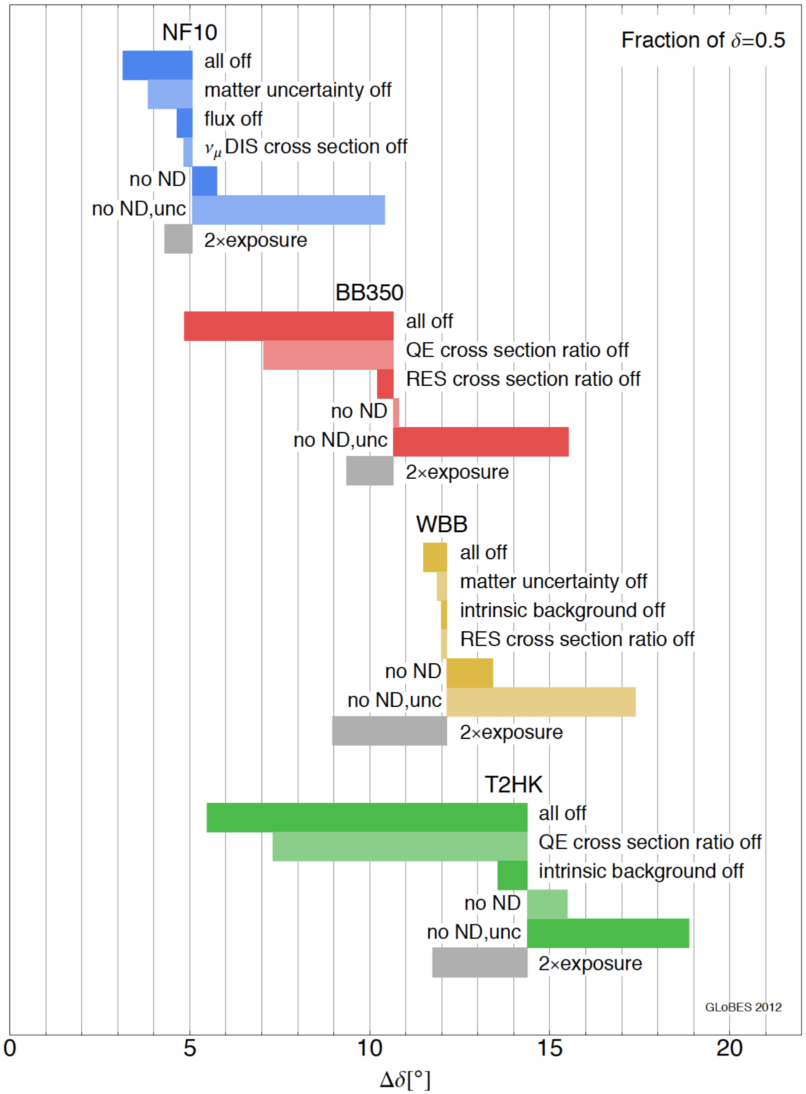


Huber *et al.*, arXiv:1411.0629v2



DUNE internal

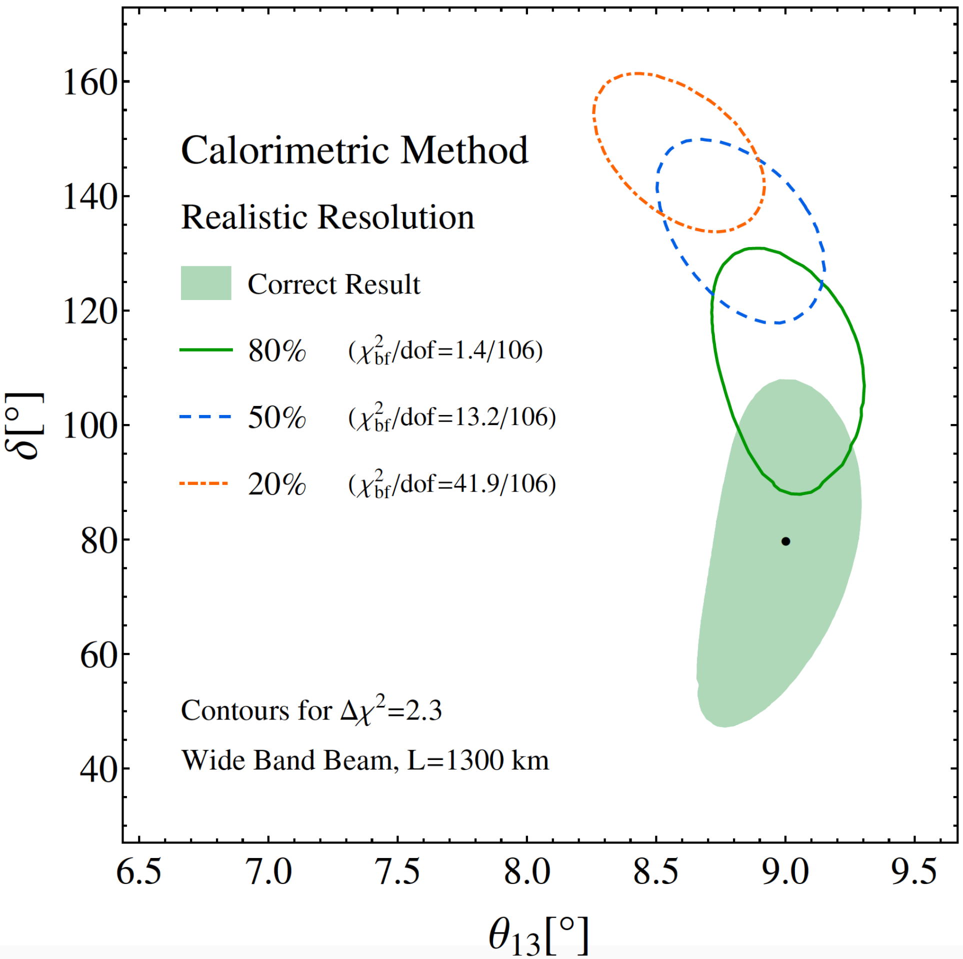
δ sensitivity & systematics



Coloma *et al*., arXiv:1209.5973v1

- Systematic uncertainties and their effect on Δδ
  - NF maintains the ~X2 improvement over WBB (DUNE)
    - Major systematic is matter effect
    - only experiment where the final flavor cross section can be determined in a self-consistent way from the disappearance data.
  - WBB robustness depends on E_ν
    - >~2 GeV, (DUNE) systematics robust from this analysis
    - <~1 GeV (HyperK) knowledge of QE cross-sections dominates

Missing the mark II



Ankowski *et al.*, arXiv:1507.08561v1

- Plot to right shows the affect on determining δ if the missing E in an event is underestimated by 20%, 50% and 80% in a "DUNE-like" detector
- Near detectors and test beam will help, but a more accurate understanding of ν interactions may be needed
- This is a detector effect and, of course, applies to all facilities.
  - However, the NF has the advantage of the Golden Channel
    - Muon neutrino final state
      - Flexibility/Robustness

Some Hypotheticals

- SνM is incomplete
  - New physics
- ν interaction physics studies lead to surprises

The SνM is incomplete
Non-standard Interactions (NSIs)

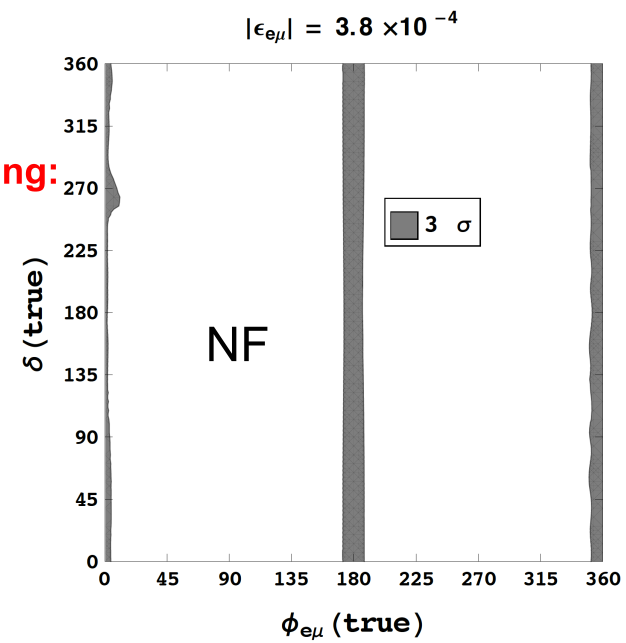
- Neutrino masses and mixing are not the only way to change flavor; this can also arise via non-standard interactions (NSIs) of neutrinos.
  - Neutrino oscillation experiments are also sensitive to flavor non-conservation due to NSIs.
  - And if NSIs exist, understanding ν mixing and CP requires additional care
- The NF adds significantly to studies involving NSIs

NSI at the NF

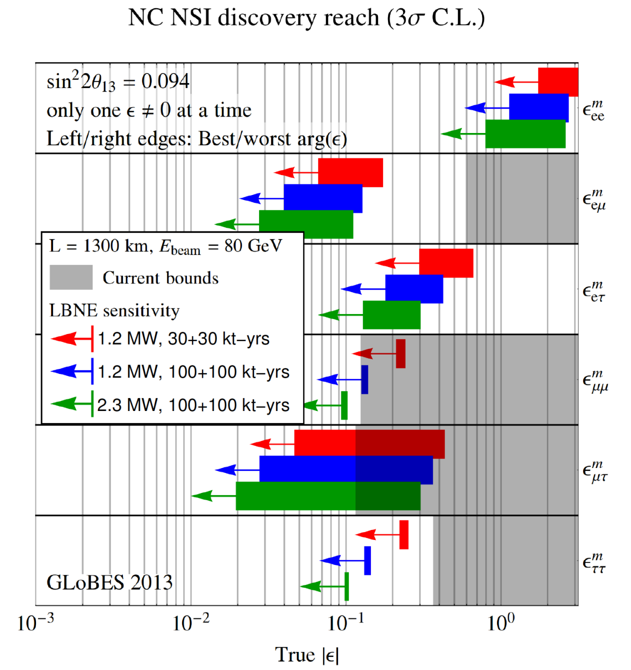
NF provides ~ 10X improvement in sensitivity

	Sensitivity w/o ν_τ ND	Sensitivity w/ ν_τ ND	Current bound [128, 162]
$\epsilon^s_{e\tau}$ $(\mu \to e\nu_\mu\nu_\tau)$	$4 \cdot 10^{-3}$	$7 \cdot 10^{-4}$	$3.2 \cdot 10^{-2}$ $(1.8 \cdot 10^{-3})$
$\epsilon^s_{\mu\tau}$ $(\mu \to e\nu_e\nu_\tau)$	$4 \cdot 10^{-1}$ $(3 \cdot 10^{-3})$	$6 \cdot 10^{-4}$ $(6 \cdot 10^{-4})$	$3.2 \cdot 10^{-2}$ $(1.9 \cdot 10^{-3})$

Truth in Advertising: HE NF



LBNE Science Report



Unshaded regions correspond to CP violation discovery reach with NSIs.
In general for NSIs < 1, the CP violation discovery reach is better in the NF

Rahman *et al.*, arXiv:1503.03248v1

The SνM is incomplete II

- New reactor, SBL, cosmic experiments confirm that there is something new
  - Multiple sterile neutrinos
  - Mass-varying neutrino
  - CPT violation
  - ????
- Will need
  - Access to as many channels as possible
  - Large L/E coverage
  - Muon source of neutrinos will help greatly
    - It would likely dominate the exploration of this new physics, if the facility existed

"*New*" concept: Hybrid NF

- This is where a facility like or similar to nuSTORM shows its strengths
- But, what do you mean by "Hybrid"?
- nuSTORM produces ν beams from μ decay as in the conventional NF

$$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \ \nu_e$$

$$\mu^- \rightarrow e^- \nu_\mu \ \bar{\nu}_e$$

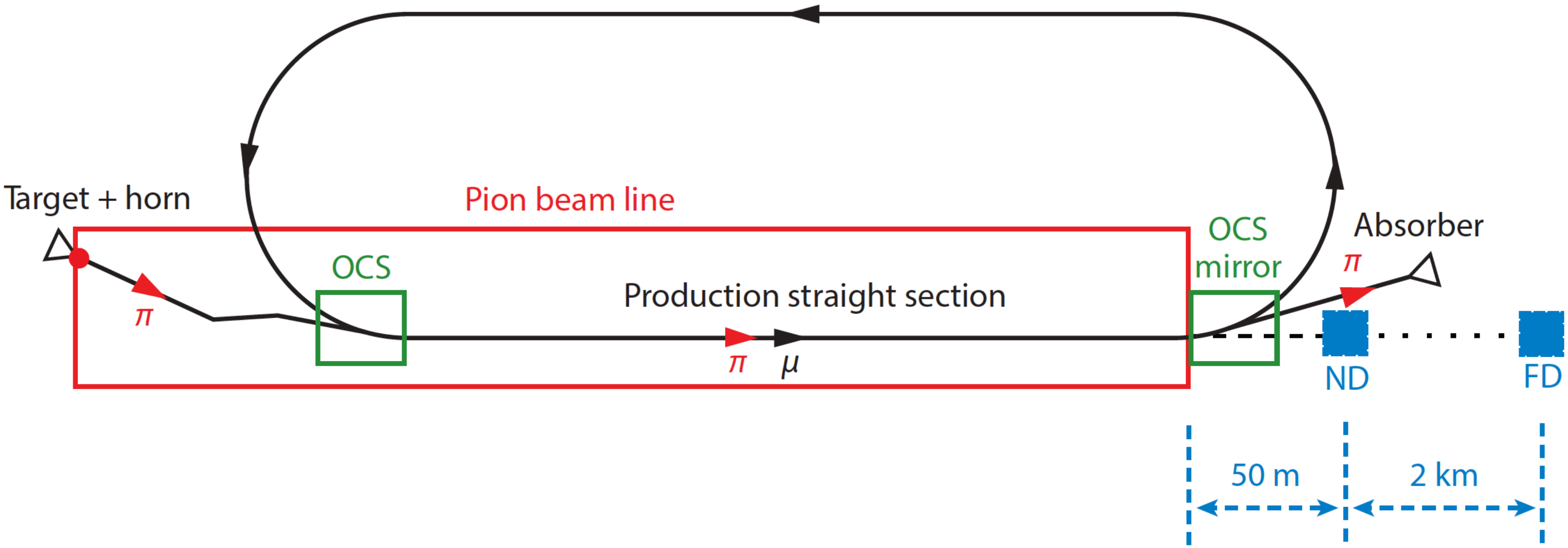
- But, it also produces a ν beam from π decay:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

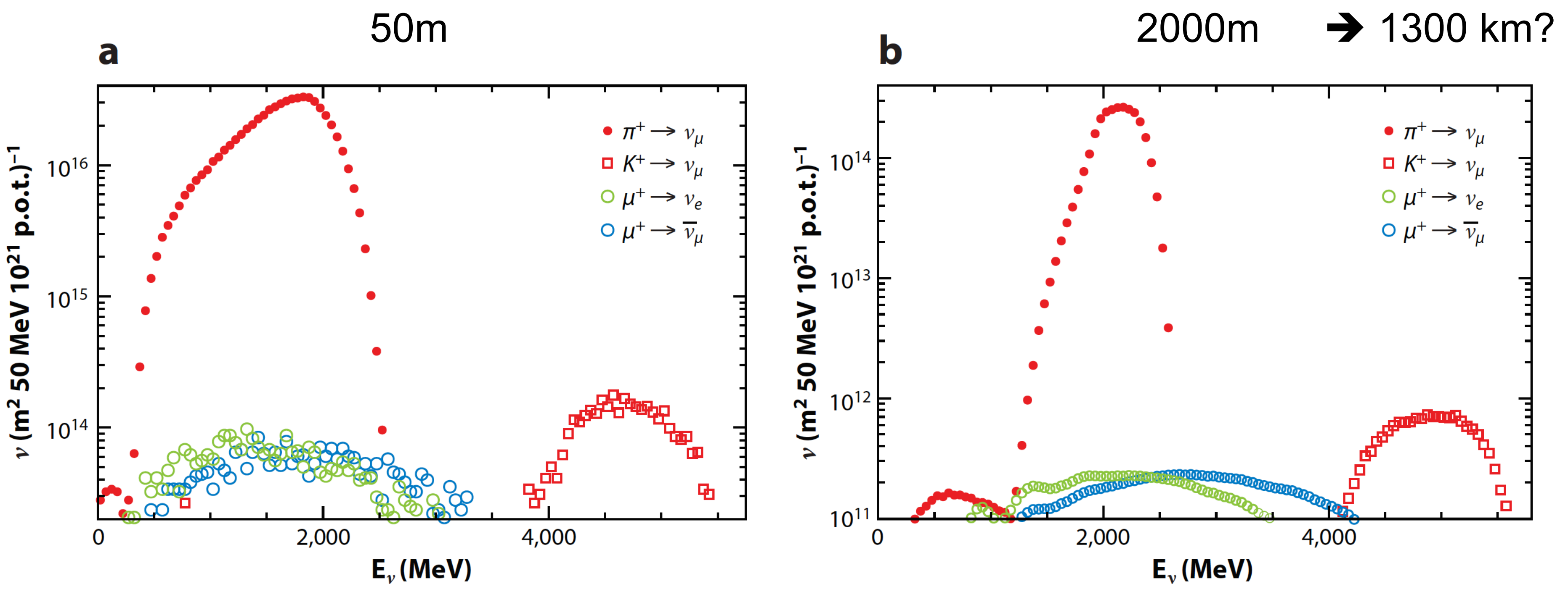
Hybrid NF layout

No cooling or acceleration



ν_s from π and μ decay separated in time

ν beams from π decay in a μ storage ring



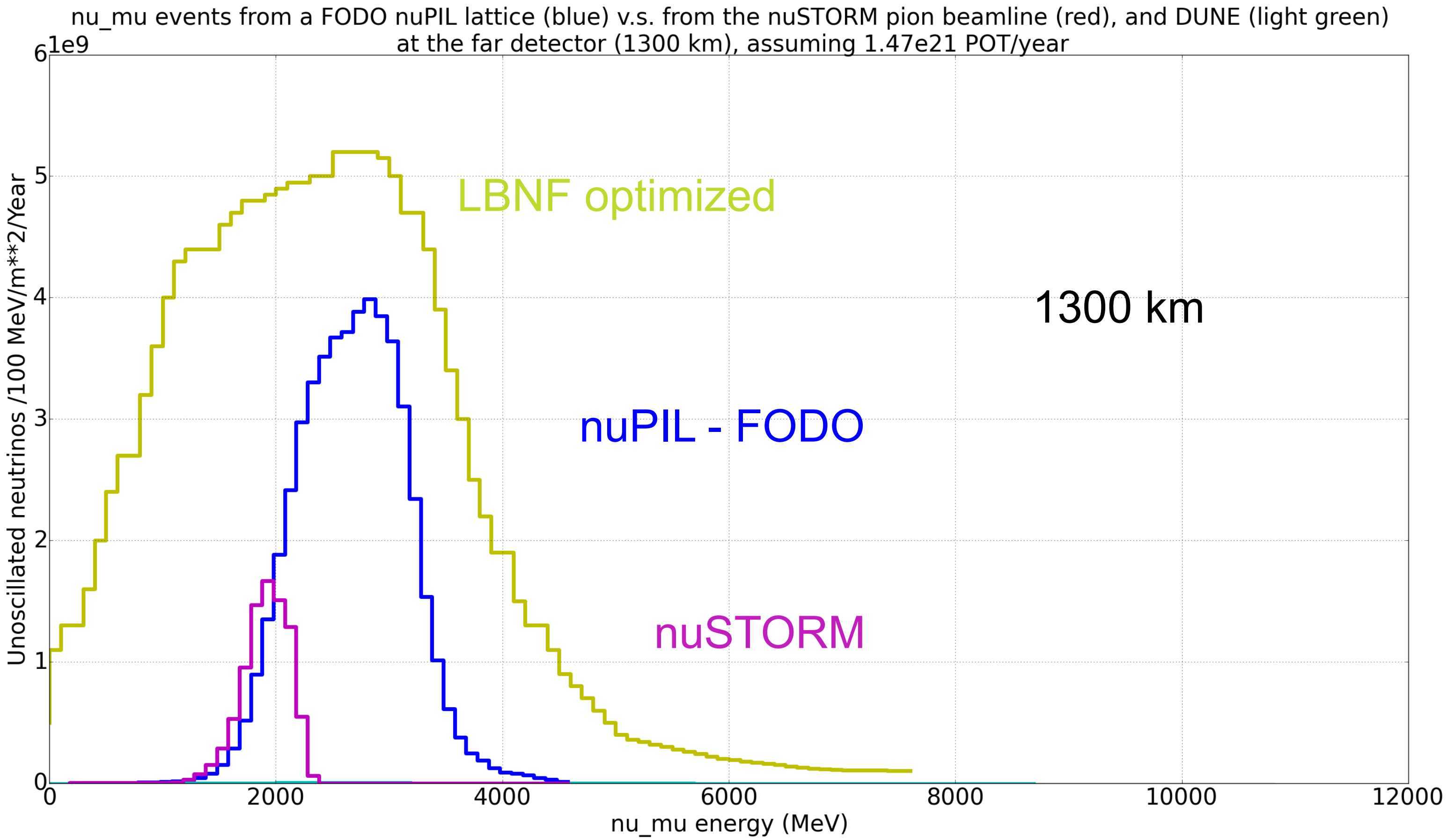
Note: Zero ν-bar from π^- decay (& vice versa)

High-energy flavor-pure ν_μ beam

Characterized at the 0.3 – 0.5% level

An interesting aside
neo-conventional ν beam

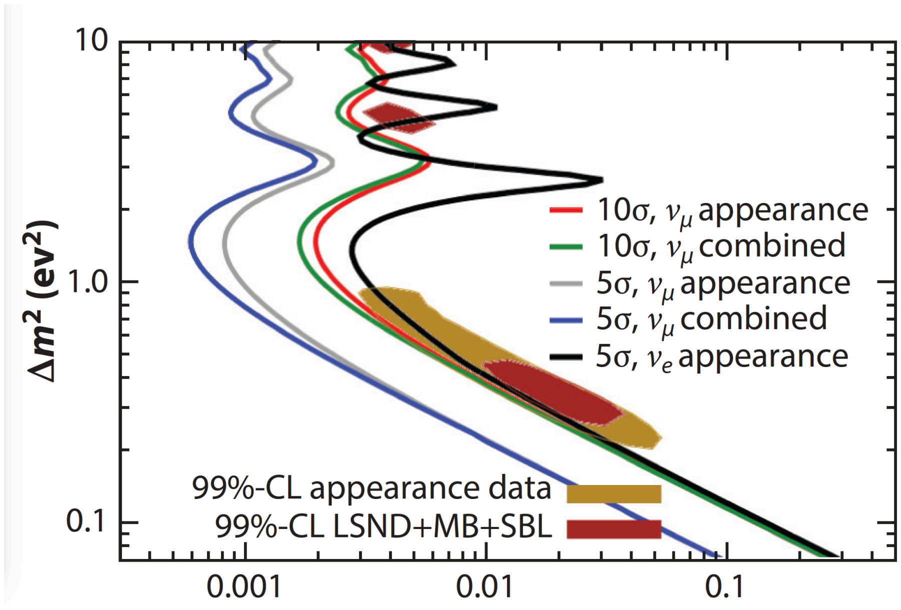
ν_μ-bar from pion injection beam line. Backgrounds not shown



See JB Lagrange's talk tomorrow afternoon in the WG3 parallel session

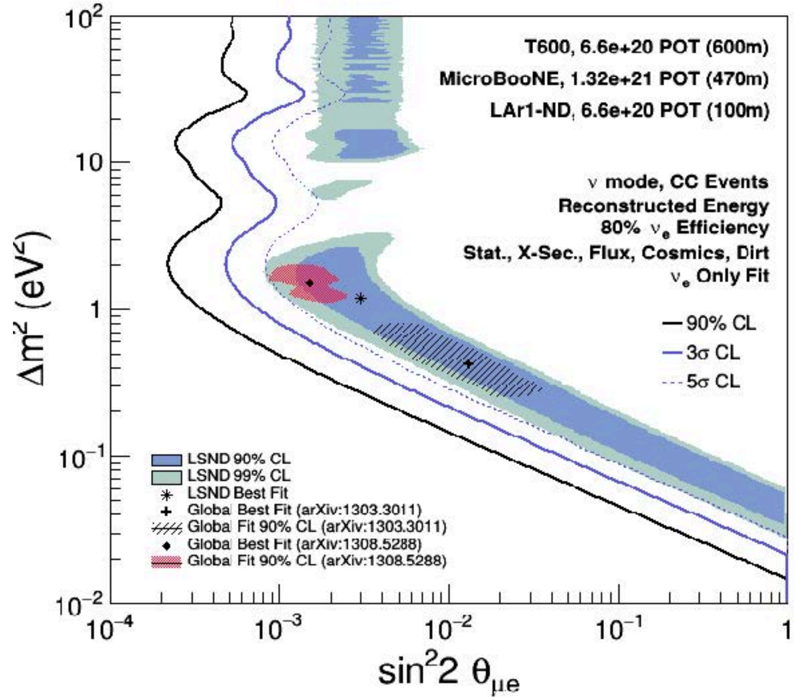
Coverage for steriles

Annual Reviews of Nuclear and Particle Science, Volume 65, Adey *et al.* nuSTORM



~8% ν_e eff.

Peter Wilson, presented at Fermilab PAC meeting June, 2015 SBN



nuSTORM does almost as well at SBN for ν_e appearance, but with a detector decidedly NOT optimize for ν_e interactions

What this points to are the potential advantages of "beam-based" source for ν_s as opposed to one where the parents are in a decay pipe

ν interaction physics

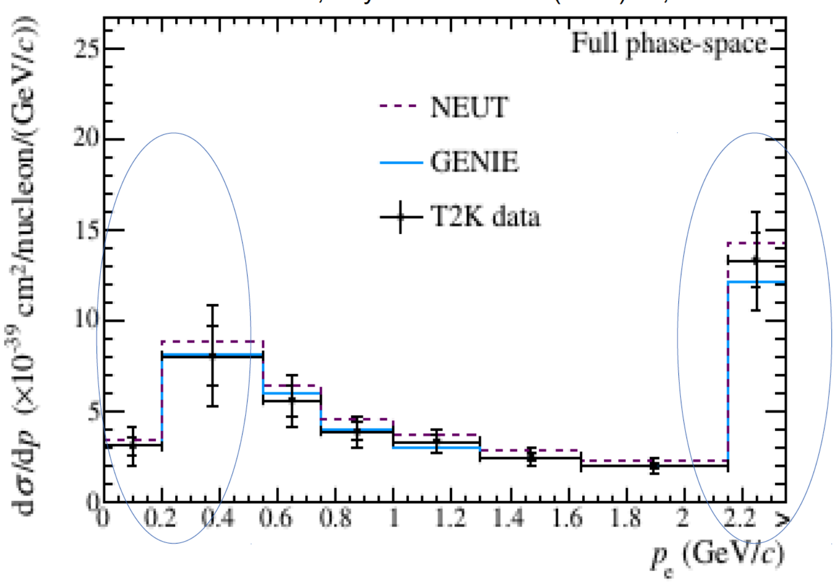
- Although the near-detector physics program at future LBL experiments, plus new dedicated experiments such as CAPTAIN, nuPRISM, plus the ongoing data taking in Minerνa, T2K, NOνV appears to have a good handle on what is needed to support the oscillation physics
- Reaching 1% precision will still be hard
  - Especially for ν_e
- & what if there are surprises/puzzles
  - Differences between ν_e and ν_μ are larger than expected
    - Day and McFarland: arXiv:1206.6745v2

New definition of high-statistics ν interaction data

Table 4 Event rates at 50 m from the end of the decay straight section per 100 T for 10^{21} OT[a]

μ^+ stored channel	k events	μ^- stored channel	k events
ν_e CC	5,188	$\bar{\nu}_e$ CC	2,519
$\bar{\nu}_\mu$ CC	3,030	ν_μ CC	6,060
ν_e NC	1,817	$\bar{\nu}_e$ NC	1,002
$\bar{\nu}_\mu$ NC	1,174	ν_μ NC	2,074
π^+ injected channel	**k events**	**π^- injected channel**	**k events**
ν_μ CC	41,053	$\bar{\nu}_\mu$ CC	19,939
ν_μ NC	14,384	$\bar{\nu}_\mu$ CC	6,986

T2K Collaboration, Phys.Rev.Lett. 113 (2014) 24, 241803



nuSTORM-like ν beam production

Beam flux/shape uncertainties ~ 0.3-0.5%

Outlook
Overview(?) to the Panel Discussion

- How do (should?) we position the field to provide new neutrino sources in the long-term - post DUNE/HyperK era? What (if anything) is needed?
  - Full blown NF, variants or simplifications of IDS-NF/NuMAX?
- In the mid-term, will we need new sources to understand a potential neo-SνM?
- Is the field of ν interaction physics fully served by conventional ν beams & will they provide the required input for the LBL experiments?
  - IF not, what is the best approach forward what is the target time frame?
- Should there be consideration to changing the approach for ν beam production for the next LBL experiments?
  - Near-term (i.e., NOW)

Thank You

Questions, comments, rebuttals, rants?

All welcome

Or save them for the panel